

1 Global ghost imaging

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10 Abstract: Ghost imaging (GI), as a novel imaging technique, offers significant potential compared to standard imaging. However, the inability to achieve large field of view, high-resolution, and high-quality image reconstruction within a short time frame and with a limited number of measurements severely hampers the practical application of ghost imaging. We propose global ghost imaging (GGI) to try to solve the above problems to realize the practicality of ghost imaging. Global ghost imaging executes hundreds of ghost imaging as subsystems at the same time. Many bucket detectors are placed in the object arm to form an array, and position sensitive detectors are placed in the corresponding positions in the reference arm. Then, a prior knowledge is introduced, but instead of calculating independently within each local system, the global prior is used to cover all subsystems. The speckle patterns of each ghost imaging subsystem are uploaded to the terminal for unified iterative operation, so that the iterative sparse solution of each subsystem changes from local optimization to global optimization. Simulation and experiments show that the global ghost imaging can achieve large field of view and high-resolution imaging, completely eliminate the discontinuity between subsystems, greatly improve the image quality, have strong noise robustness ability, and more importantly, it can achieve image reconstruction with ultra-low number of measurements. Using the classical ghost imaging framework and the computational ghost imaging framework respectively, we show that this method has the ability to reconstruct complex samples with 800×280 pixels in only 8 measurements.

28 1. Introduction

29 Ghost imaging (GI), i.e. correlation imaging, is a new type of imaging technology based on the correlation characteristics of quantum entanglement [1, 2] or classical light field fluctuations [3, 4], which can nonlocally obtain the information of the target object through the intensity correlation between the reference arm and the object arm. Ghost imaging provides a method that is difficult to obtain clear images by conventional means, and can solve some problems that are not easy to solve by conventional imaging. Ghost imaging has been applied in military, radar detection and optical encryption. It can also be further applied in pathological analysis, material research, life science and material science in the future. GI has been proved to be suitable for classical thermal light sources [3, 4]. Furthermore, it has also been proved to be suitable for atoms [5], electrons [6], neutrons [7, 8] and X-ray [9–13]. Computational ghost imaging (CGI) [14] uses a spatial light modulator (SLM) to modulate the light field, eliminating the steps of recording structural illumination, thus forming a system architecture consistent with single pixel imaging (SPI).

42 However, ghost imaging requires thousands of measurements to reconstruct a large field of view and high-resolution image, and each acquisition requires a completely different mask to be replaced, both of which are time-consuming. Many measurements and long experimental time have caused serious difficulties for the practical application of ghost imaging. It may take tens of thousands of measurements to reconstruct a result with 256×256 pixels and take several hours or even longer. In order to solve this problem, various ghost imaging technologies try to mine

the information buried in the dual arm signal from various dimensions to reduce the number of measurements required to reconstruct high-quality images. Reconstruction algorithms can be divided into three categories according to the type of iteration, including linear non iterative methods (e.g. traditional ghost imaging (TGI), differential ghost imaging(DGI) [15] and normalized ghost imaging(NGI) [16]), linear iterative methods (e.g. gradient descent-GD) and nonlinear iterative methods (e.g. total variation augmented Lagrangian alternative direction algorithm-TVAL3 [17]). By adding light intensity fluctuation correction, digital mask sorting [18, 19] and compressed sensing [20, 21] and other methods, the existing GI methods have made full use of the object information contained in each pixel, and it seems difficult to further reduce the number of measurements required for high-quality imaging without changing the experimental architecture.

Here, we propose global ghost imaging (GGI) from the perspective of convex optimization. This method is no longer confined to the information inside the local system. Hundreds of bucket detectors are placed close to each other in the object arm to form an array, and hundreds of ghost imaging measurements are performed at the same time. The information of various dimensions and each iteration in each subsystem are shared and coordinated globally. In each iteration of each ghost imaging subsystem, not only the object information in the subsystem is the source, but the results of all subsystems in the global domain of the previous iteration are used as a reference to jointly find the gradient statistical sparse optimal solution of the sample image globally, so that each ghost imaging subsystem is no longer in the local optimal trap. This method not only greatly improves the image quality, but also reduces the noise of the reconstruction results. Since the ghost imaging subsystems share the same regularization prior globally, the strong discontinuity at the junction of each subsystem is no longer generated from the underlying mechanism. The prior unification in the global domain and the interactive iterative operation between subsystems further significantly reduce the number of sampling required for high-quality imaging. Simulation and experiments using classical ghost imaging framework [22–26] and computational ghost imaging framework [27] verify the ability of this method to reconstruct complex samples with 280×800 pixels in only 8 measurements. This will greatly reduce the dose required for X-ray imaging, and shorten the whole experimental process to 10 seconds or so. Computational ghost imaging framework can save the time-consuming reference arm recording process, which can further reduce the total experimental time by more than half. We believe that this research will provide a new framework for ghost imaging, which will greatly promote the practical process of ghost imaging.

2. Principle, universal interface and simulation experiment

In the framework of global ghost imaging experiment, each ghost imaging subsystem can be simply written as a linear system:

$$\begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_n \end{bmatrix} = \begin{bmatrix} A(1,1) & A(1,2) & \cdots & A(1,m) \\ A(2,1) & A(2,2) & \cdots & A(2,m) \\ \vdots & \vdots & \ddots & \vdots \\ A(n,1) & A(n,2) & \cdots & A(n,m) \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_m \end{bmatrix} \quad (1)$$

Where $A \in R^{n \times m}$ is the mask modulation matrix, that is, the speckle pattern. $x \in R^{m \times 1}$ is the object image, which is the unknown variable we need to solve. $b \in R^{n \times 1}$ is the bucket detection signal sequence. m is the number of image pixels and n is the number of measurements. This subsystem can be abbreviated as $Ax = b$. The essence of ghost imaging is to solve a system of underdetermined linear equations. All ghost imaging methods are committed to mining the

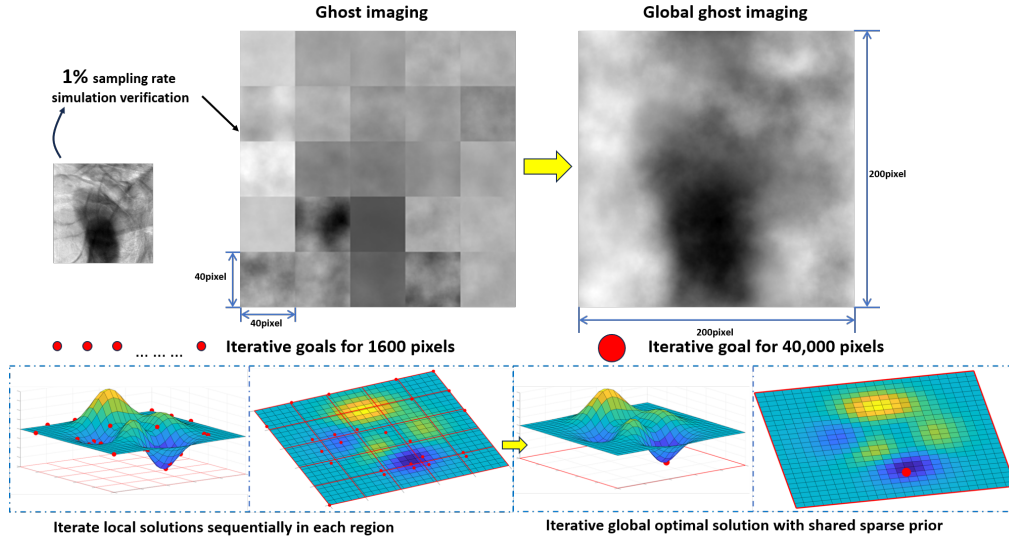


Fig. 1. Schematic diagram of global ghost imaging principle; modifying GI algorithm to implement GGI.

89 information of objects from the modulated light field A and single pixel signal b as much as
 90 possible. In global ghost imaging, hundreds of bucket detectors are placed close to each other
 91 on the object arm, and the imaging process can be written as follows:

$$\begin{aligned}
 A_{1,1}x_{1,1} &= b_{1,1}; A_{1,2}x_{1,2} = b_{1,2}; \cdots; A_{1,M}x_{1,M} = b_{1,M}, \\
 A_{2,1}x_{2,1} &= b_{2,1}; A_{2,2}x_{2,2} = b_{2,2}; \cdots; A_{2,M}x_{2,M} = b_{2,M}, \\
 &\vdots \\
 A_{N,1}x_{N,1} &= b_{N,1}; A_{N,2}x_{N,2} = b_{N,2}; \cdots; A_{N,M}x_{N,M} = b_{N,M}
 \end{aligned} \tag{2}$$

92 The unknown variable of global ghost imaging, X , consists of $x_{1,1}, x_{1,2}, \cdots, x_{n,m}$ and is a vector
 93 in ultra-high dimensional space. This framework makes it possible for GGI to reconstruct large
 94 field of view results with very low measurements.

95 The schematic diagram of the principle of global ghost imaging is shown in Fig.1. This
 96 method is a concept and is not restricted to a specific algorithm. However, due to the unique
 97 bucket detector array framework of GGI, the ghost imaging algorithm cannot be directly adapted.
 98 We take TVAL3 as an example to show the principle of GGI and the method of converting GI
 99 algorithm to GGI. TVAL3 is a nonlinear iterative algorithm based on compressed sensing, which
 100 can be simply expressed as:

$$\begin{aligned}
 &\text{Min} ||c||_{l_0} \\
 &s.t. Dx = c; \\
 &Ax = b
 \end{aligned} \tag{3}$$

101 $Ax = b$ is the measurement model of ghost imaging, D is the conversion matrix, converting the
 102 object image x to c , l_0 norm calculates the number of non-zero elements in c and minimizes
 103 this index to find sparse solutions. The l_0 norm is a non-convex function and is difficult to solve.
 104 It is usually approximated by the l_1 norm. TVAL3 requires fewer iterations, has strong noise
 105 robustness and high reconstructed image quality. It is one of the most powerful ghost imaging

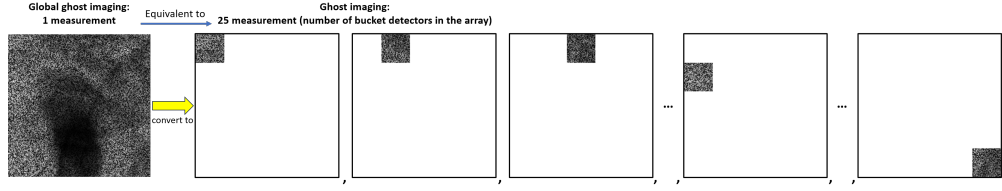


Fig. 2. More general GGI interface; reverse conversion of GGI speckle pattern to GI form

algorithms at present and has withstood the test of numerous experiments. When modified into a global algorithm, TVAL3 can be expressed as:

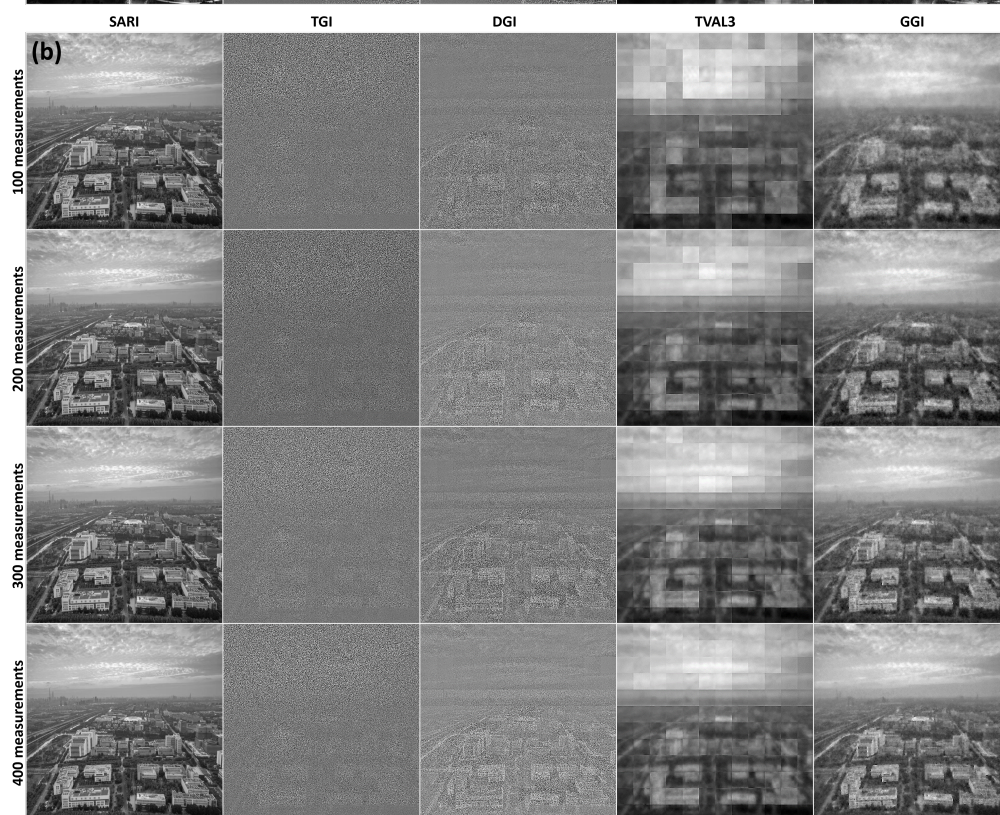
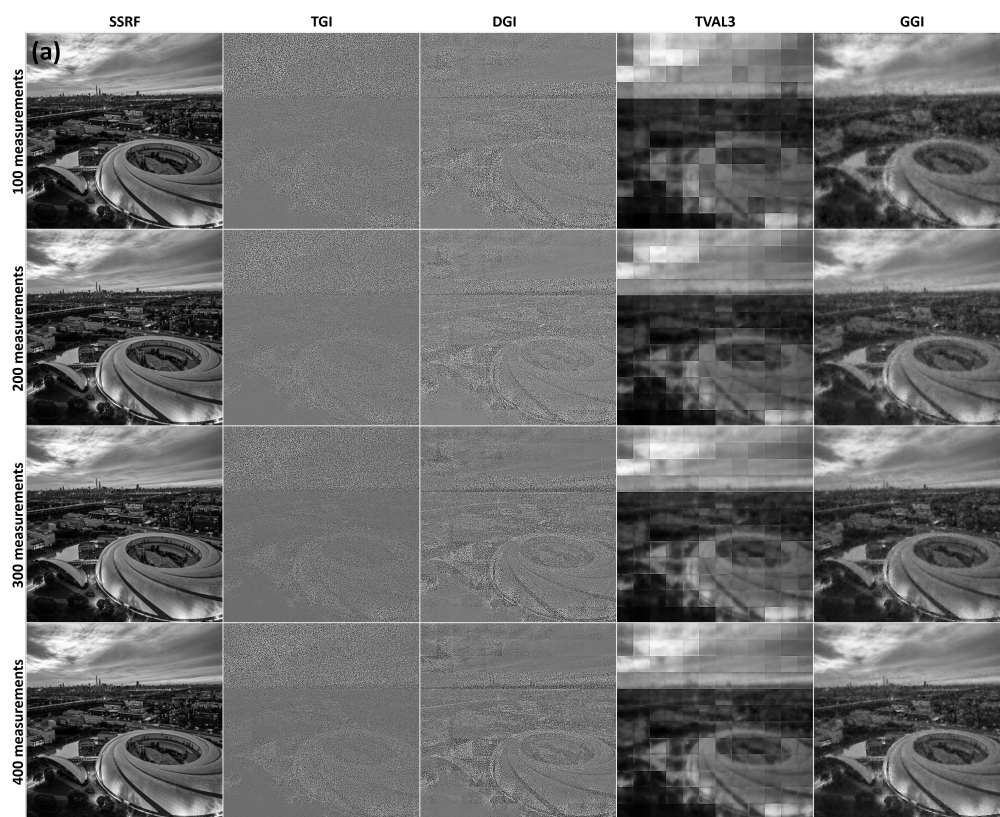
$$\begin{aligned}
 & \text{Min} \|C\|_{l_0} \\
 & \text{s.t. } DX = C; \\
 & A_{1,1}x_{1,1} = b_{1,1}; \\
 & A_{1,2}x_{1,2} = b_{1,2}; \\
 & \quad \dots; \\
 & A_{1,M}x_{1,M} = b_{1,M}; \\
 & \quad \dots; \\
 & A_{N,M}x_{N,M} = b_{N,M};
 \end{aligned} \tag{4}$$

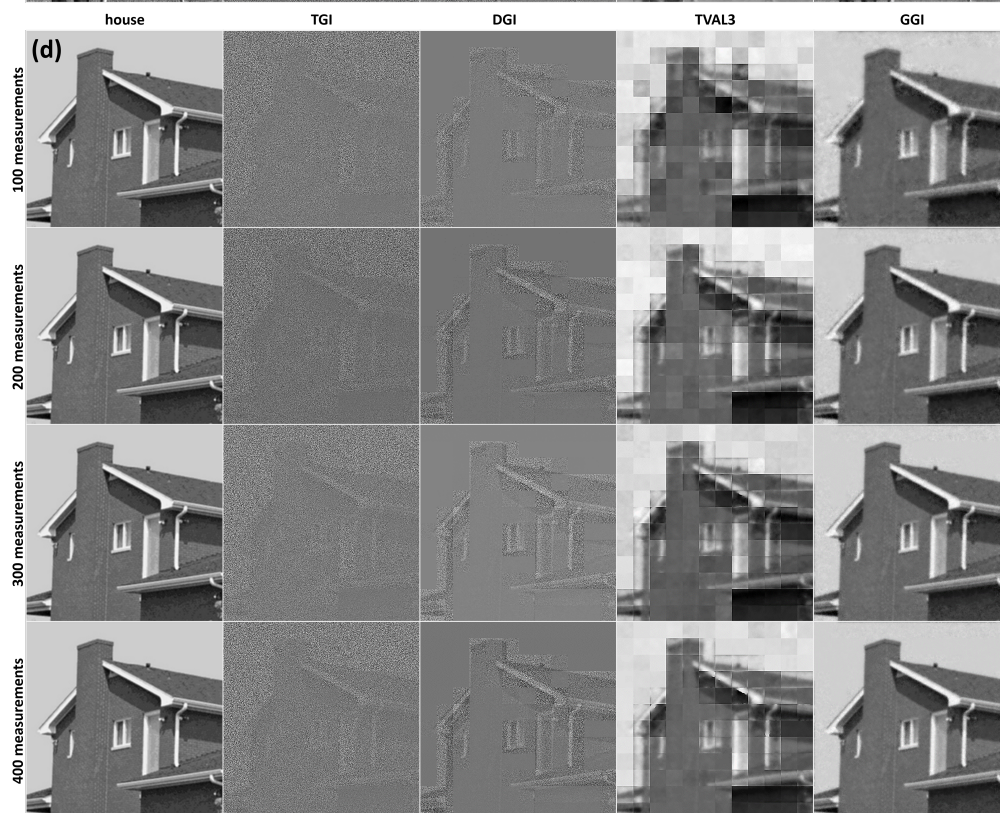
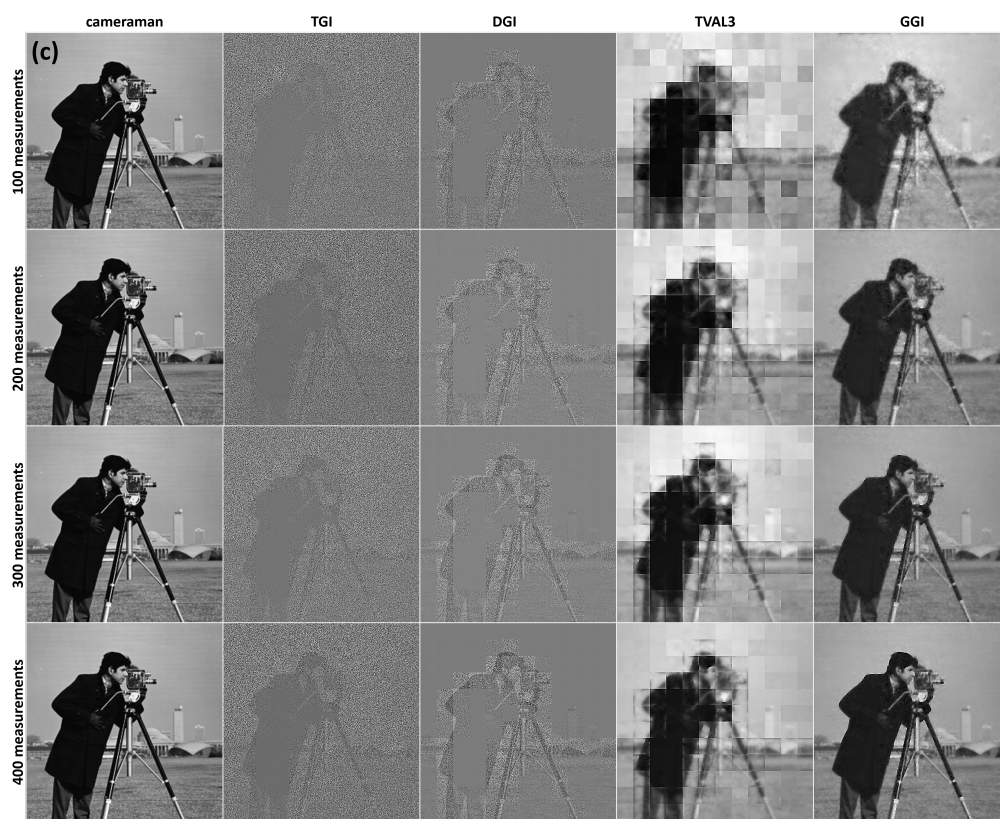
As mentioned in GGI imaging process, X is a huge variable to be solved consisting of $x_{1,1}, x_{1,2}, \dots, x_{N,M}$. Global ghost imaging adds hundreds of ghost imaging subsystem sampling processes to the limit equation, and only uses the same prior knowledge to iterate X as a whole. The Augmented Lagrange method will throw $N \times M$ constraint equations onto the iteration target, so that the whole is transformed into an unrestricted equation. This is an ultra long iteration goal with many variables, which requires a large memory space for the computer.

Global ghost imaging liberates each ghost imaging subsystem from the local optimal iteration trap, and jointly iterates to find the global optimal solution. Global ghost imaging shows powerful performance, which is stronger than all existing ghost imaging methods. We will make extensive comparison and prove this later. However, GGI still has a small problem hindering its wide application - every GI algorithm needs to be rewritten to adapt to the GGI architecture, which is annoying and time-consuming. To address this, we propose a reverse conversion method that convert the speckle patterns of GGI into GI adapted form, which is more efficient than previously adapting GI algorithms to GGI.

The schematic diagram of the reverse conversion from global ghost imaging to ghost imaging is shown in Fig.2. One measurement of global ghost imaging can be equivalent converted to $N \times M$ measurements of ghost imaging. The number of measurements increases hundreds of times while preserving large field of view, so that any GI algorithm can achieve high-quality reconstruction with a large field of view and a small number of measurements. This is equivalent to a measurement number amplification technology, which provides a universal GGI oriented interface for all GI algorithms. This will greatly reduce the use threshold of GGI and improve its versatility.

Firstly, the performance of global ghost imaging is detected in the simulation experiment without introducing experimental error. The experimental results of a series of simulated global ghost imaging are listed in Fig.3.(a-d). The target image size is 480×480 pixels. In the simulation experiment, 12×12 bucket detectors are placed in the object arm, and the image size of each ghost imaging subsystem is 40×40 pixels. In order to ensure that the simulation experiment





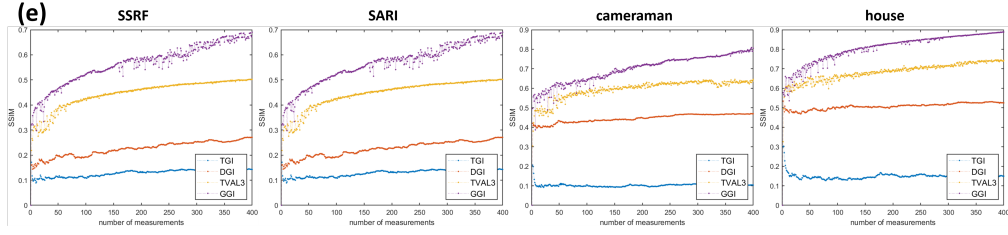


Fig. 3. Comparison of TGI, DGI, TVAL3, and GGI through simulation experiments (image size 480×480). The reconstruction was performed using (a)SSRF, (b)SARI, (c)cameraman, and (d)house as object images with measurements of 100, 200, 300, and 400, respectively. (e)SSIM between TGI, DGI, TVAL3 and GGI.

results are not affected by the random distribution fluctuation of speckle pattern, all simulation experiments use the same group of randomly distributed speckle patterns. The maximum number of measurements is 400, which means that for the traditional single pixel ghost imaging, the sampling rate is only 0.17%, which is hardly imageable, so it is no longer included in the comparison. We will use TGI, DGI and TVAL3 bucket detector array ghost imaging and GGI for comparison. The measurement numbers are 100, 200, 300 and 400 respectively. SSIM is an index to evaluate the similarity between reconstruction results and objects. The comparison of SSIM values of the four methods is shown in Fig 3.e.

Because of its low utilization of object information, TGI can only vaguely see the outline of the object in low sampling image reconstruction. DGI is a variant of TGI, and its effect has been improved. TVAL3 performs well in low sampling image reconstruction, and can reconstruct the object details in a single subsystem at 200 measurements. However, due to the introduction of priori in each local system, the image fragmentation caused by the discontinuity between subsystems is extremely serious. Especially in image reconstruction with a lower number of measurements (100), the image is completely torn by discontinuities. Global ghost imaging overcomes these defects. Without introducing experimental errors, the reconstruction results of images with large field of view not only have no discontinuities between subsystems, but also the quality of reconstructed images is much higher than that of TVAL3. At 100 measurements, even if discontinuities are ignored, the reconstruction of TVAL3 in a single subsystem is almost fail. Global ghost imaging has completed the task well, and its limit is far more than that. We will discuss it again later. The SSIM value of GGI from 2 to 400 measurements is much higher than that of other methods, which strongly supports the above statement.

3. Experimental setup, speckle analysis, experimental results and reconstruction of ultra-low measurement number

In response to the demand for beam splitting in X-ray ghost imaging, we have built a crystal beam splitting system at the X-ray testing line station BL09B [28] of Shanghai Synchrotron Radiation Facility (SSRF) to achieve global ghost imaging in a classical framework. To achieve high-quality spatial intensity correlation beam splitting, we have developed a crystal beam splitter [22–26] specifically designed for XGI. The beam splitter is a 300 μm thick Laue diffraction crystal developed, with a diffraction Bragg angle of 5.67° . The photon energy during the experiment is 20keV. X-rays pass through the copper foam to create a speckle pattern. The splitter divides the modulated beam into two beams in the reference arm and the object arm, with an intensity ratio of 16:1. The developed beam splitter can achieve beam splitting with a large field of view, and the beam splitting correlation can reach 0.9 or above. The position sensitive detector (OnSemi KAI-16000) will simultaneously record two beams, with the weaker beam being manually fitted

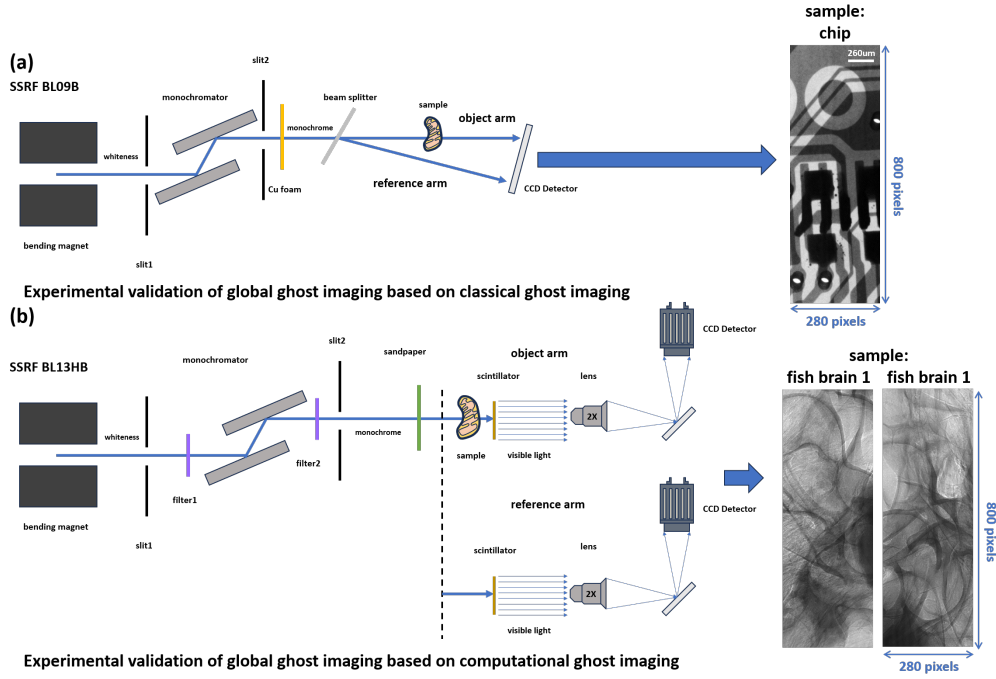


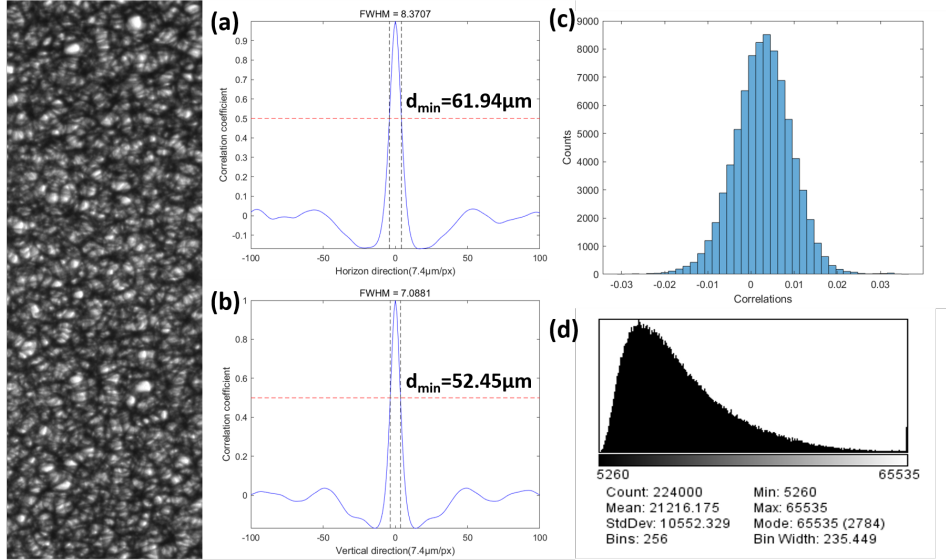
Fig. 4. (a)Experimental platform for GGI based on classic ghost imaging framework at BL09B. (b)Experimental platform for GGI based on computational ghost imaging framework at BL13H B.

170 into a bucket detector array. The effective area of the CCD detector is $36 \times 24\text{mm}^2$, with a pixel
 171 size of $7.4 \mu\text{m}$. The schematic diagram of the experimental setup is shown in Fig.4.(a) .

172 In order to more systematically and comprehensively verify the performance of global ghost
 173 imaging, we also built a virtual beam splitting system at the X-ray imaging and biomedical appli-
 174 cation beamline BL13HB [29] of SSRF to achieve global ghost imaging within the framework
 175 of computational ghost imaging. The modulator consists of 7 layers of 200 mesh sandpaper, and
 176 the motor carrying the sample moves in and out the beam to record the object arm and reference
 177 arm. The bucket detector array is also artificially fitted. The photon energy during the experi-
 178 ment was 15keV. The imaging system consists of a 100um thick scintillation crystal (LuAG: Ce),
 179 an optical conversion microscope (model: Optique Peter MICRX016), and an sCMOS detector
 180 (Hamamatsu ORCA Flash 4.0 C11440). The effective area of the detector is $6.6 \times 6.6\text{mm}^2$, with
 181 a pixel size of $3.25 \mu\text{m}$. The experimental setup is shown in Fig.4.(b) .

182 Because the resolution of the reconstruction results cannot be smaller than the minimum effec-
 183 tive features of speckle patterns, speckle patterns have a decisive impact on the reconstruction
 184 quality of ghost imaging, quantification and discussion of them are necessary. For classical
 185 ghost imaging, the thickness of modulator foam copper is about $300 \mu\text{m}$, the aperture is between
 186 $150 \mu\text{m}$ and $190 \mu\text{m}$, and the average voidage is about 77.4%. The full width at half maximum
 187 (FWHM) of the point spread function (PSF) is $61.94 \mu\text{m}$ horizontally (Fig.5.(a)) and $52.45 \mu\text{m}$
 188 vertically (Fig.5.(b)). For calculating ghost imaging, the hole size of the modulator sandpaper
 189 is $70 \mu\text{m}$, and the FWHM of PSF is $29.23 \mu\text{m}$ in the horizontal direction (Fig.5.(e)) and 29.45
 190 μm in the vertical direction (Fig.5.(f)). The X-ray modulation capabilities of the above two are
 191 shown in Fig (d) And (h), the modulation ability of copper foam is stronger. The minimum effec-
 192 tive characteristic of sandpaper is smaller than that of copper foam, but because the modulation

Speckle patterns of classical ghost imaging-Copper foam



Speckle patterns of computational ghost imaging-Sandpaper

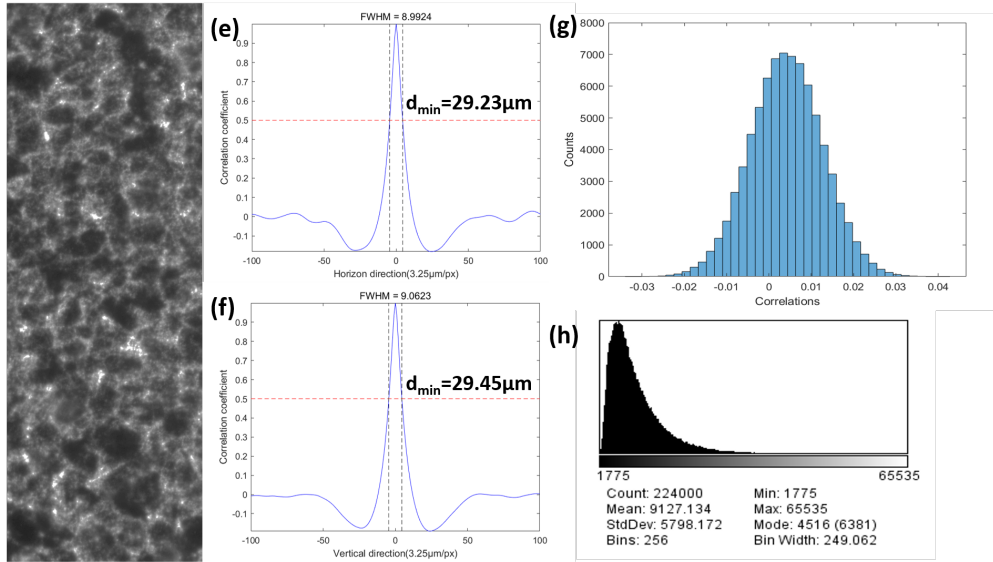


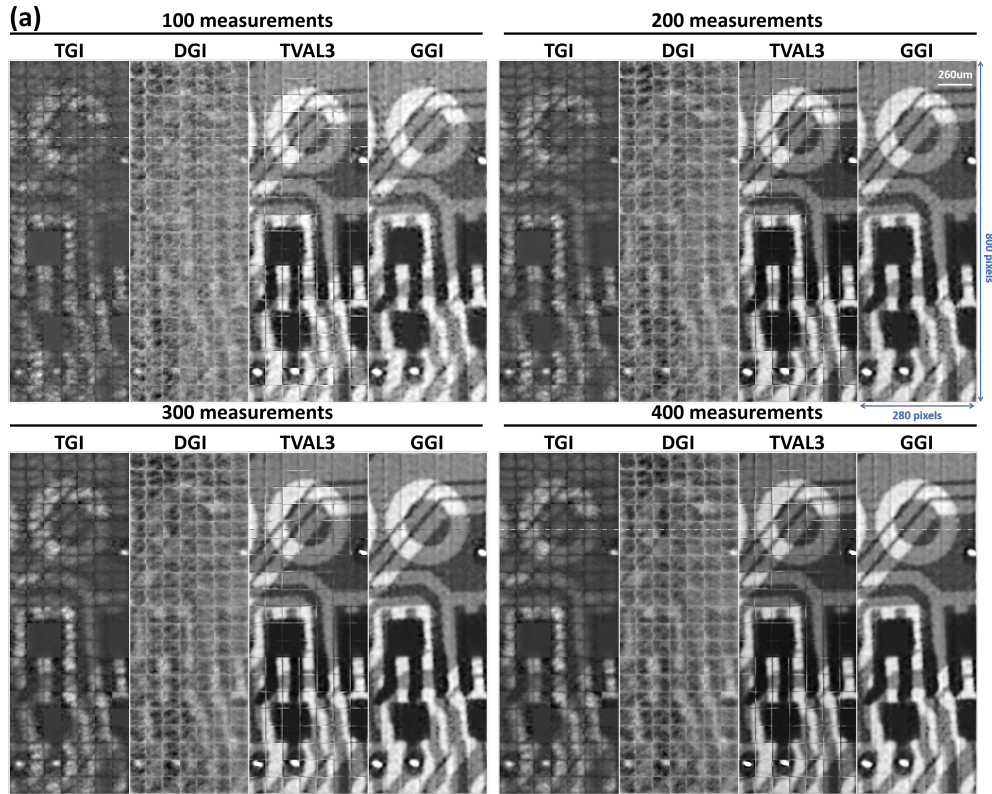
Fig. 5. Speckle analysis—copper foam and sandpaper; The FWHM of PSF in horizontal(a,e) and vertical(b,f) directions; (c,g)Statistical histogram of speckle patterns correlation; (d,h)Statistical histogram of speckle patterns correlation

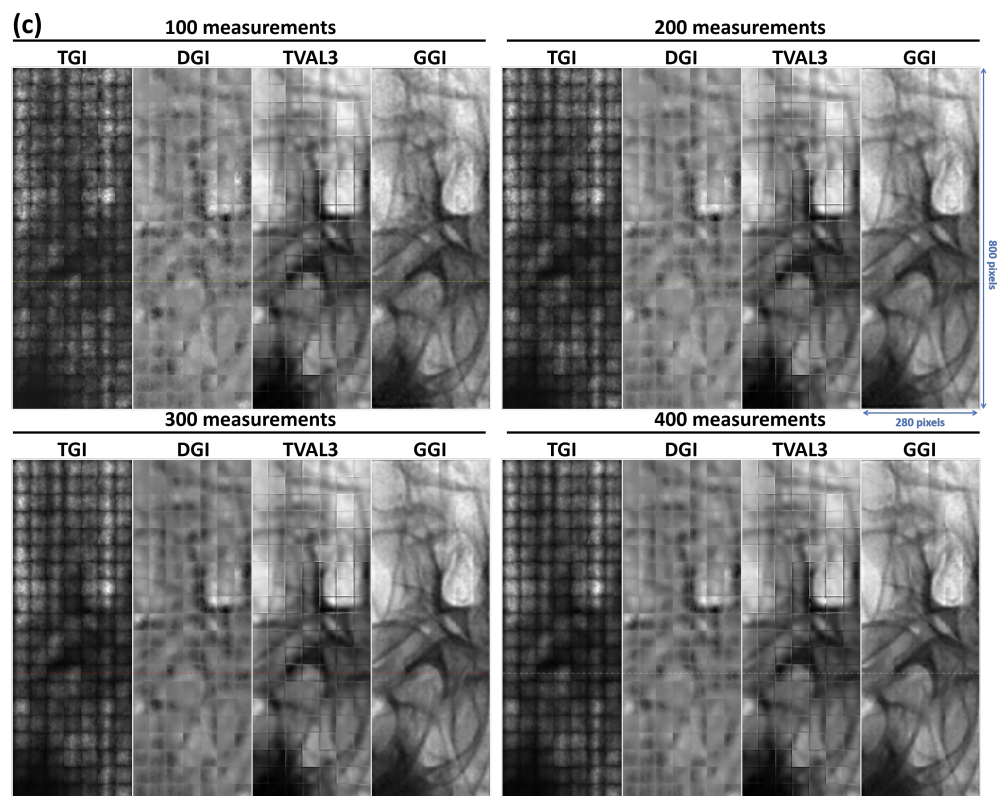
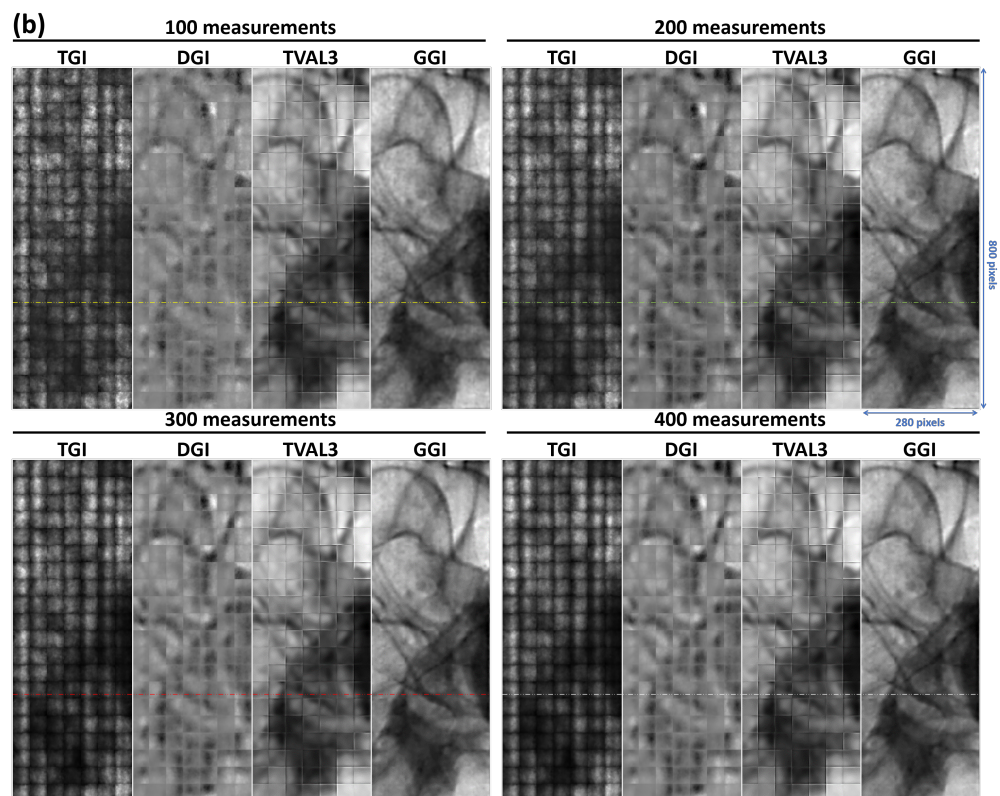
193 ability of sandpaper is weaker, copper foam is more suitable for higher energy experiments.

194 The quality of reconstruction results is also affected by the degree of correlation between
 195 speckle patterns. If there are speckles that can be represented by linear superposition of other
 196 speckle patterns, it is considered invalid sampling. The statistical histogram of the correlation
 197 between any combination of two speckle patterns (C_{400}^2) is shown in Fig (c) And (g), the copper
 198 foam is more uncorrelated, and both can approximately regard the random speckle patterns as
 199 orthogonal to each other.

200 In the classic ghost imaging framework, we use chips as sample. In the computational ghost
 201 imaging framework, in order to challenge the ultimate ability of global ghost imaging, fish brains
 202 with high complexity and low absorption contrast were selected as samples. The object image
 203 size is 800×280 pixels, and the image size of a single ghost imaging subsystem is 40×40 pixels.
 204 The results of the experimental verification are listed in Fig.6.(a-c), and the comparison graphs
 205 of SSIM values and cross-sectional lines with increasing measurement numbers are located in
 206 Fig.6.(d). Experimental results have shown that GGI using crystal beam splitting scheme and
 207 virtual beam splitting scheme both have higher imaging quality than other methods, without any
 208 discontinuity caused by independent measurements between subsystems. This enables ghost
 209 imaging to reconstruct large-sized, high-quality, and high-resolution images with fewer samples.

210 An interesting phenomenon was discovered in the experiment. Because of the short wave and
 211 strong penetration of X-ray, the beam splitter cannot divide the beam into two identical beams.
 212 This means that the speckle patterns of the reference arm and the object arm are not exactly the
 213 same in the classical framework, which not only leads to the inconsistency of the FWHM of PSF
 214 in Figure a and Figure b, but also results in poorer reconstruction quality of DGI compared to
 215 TGI only in experiments with chips as samples.





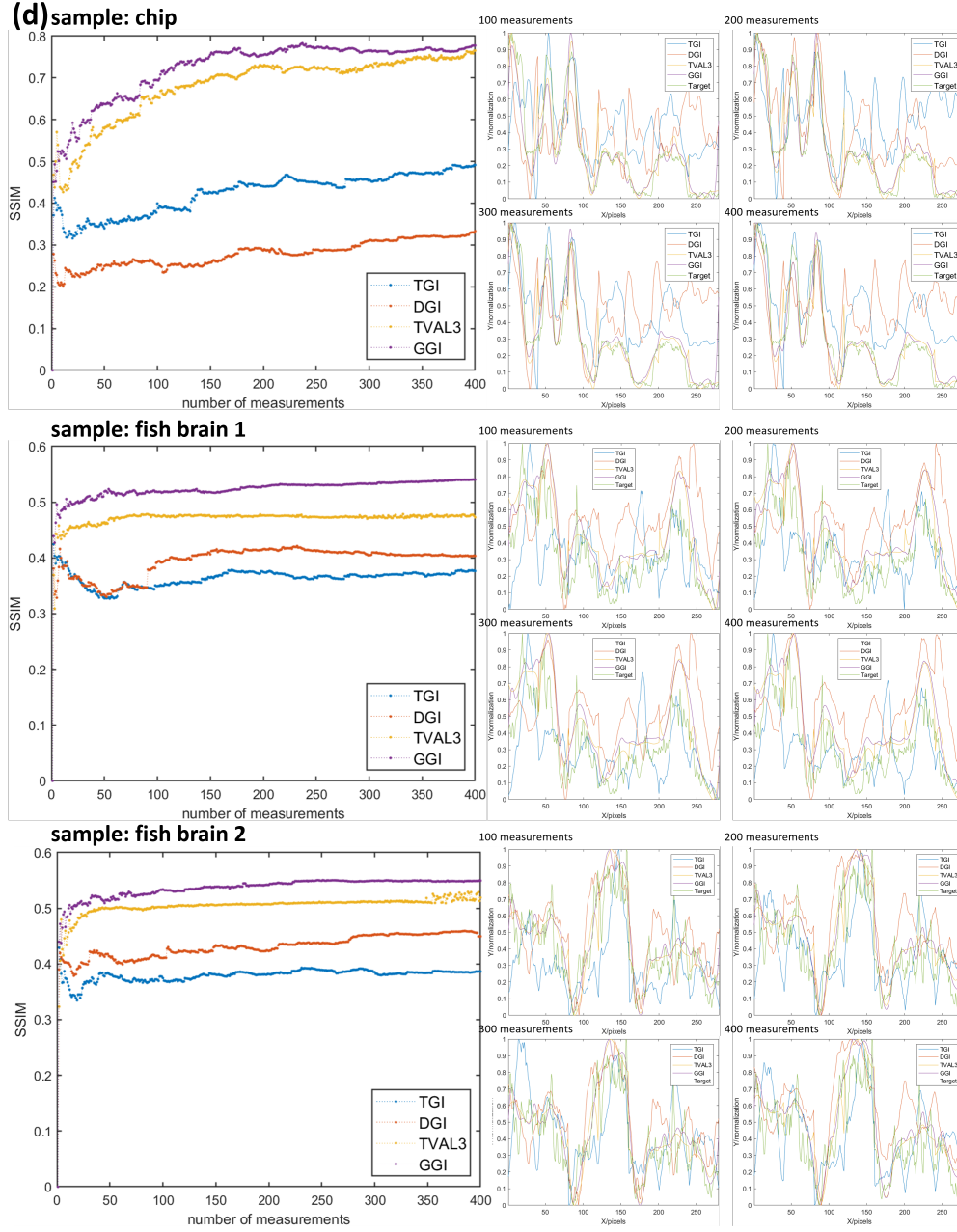
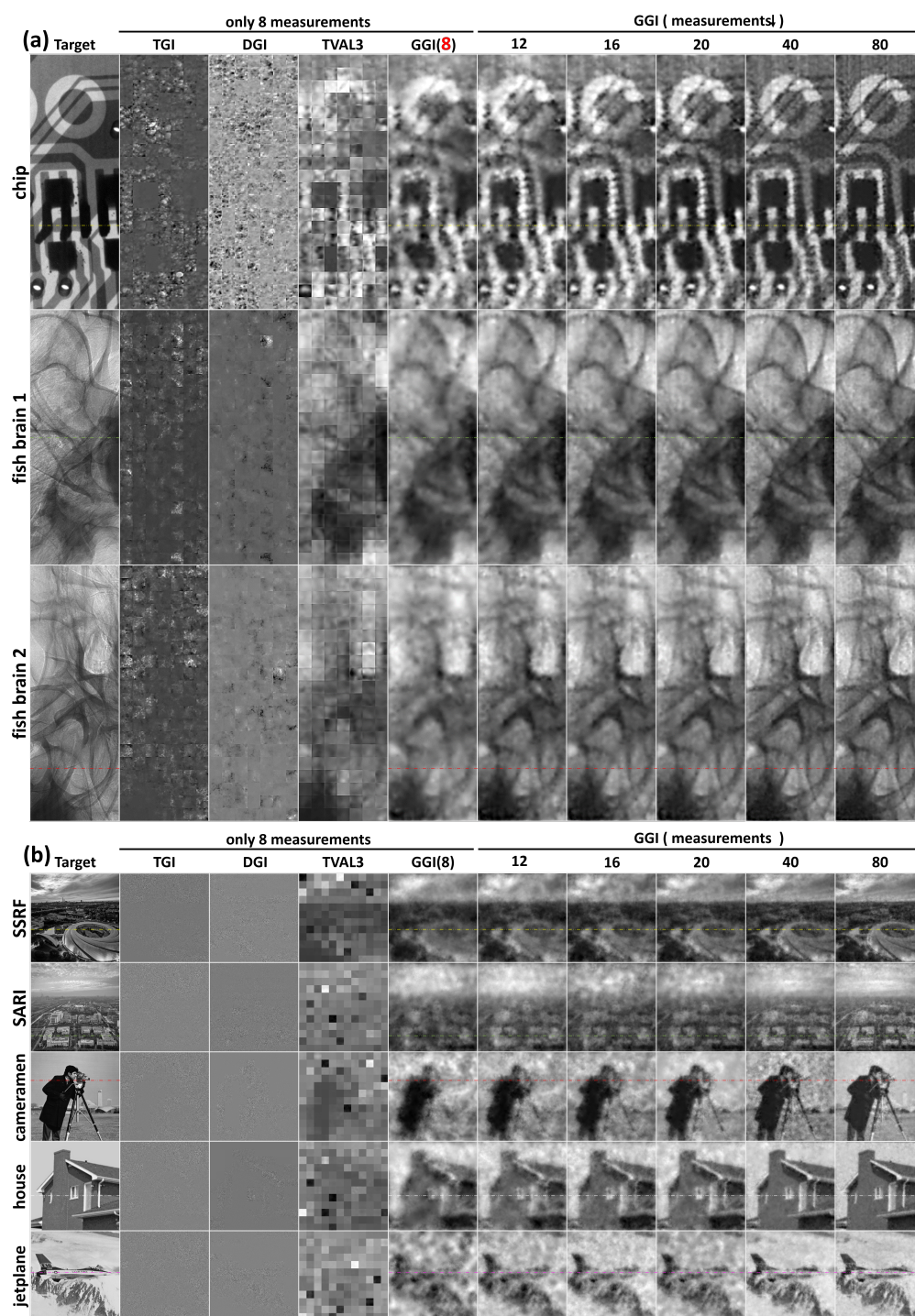


Fig. 6. Comparison of TGI, DGI, TVAL3, and GGI through experiments (image size 280×800). (a)chip, 20keV; (b)fish brain1, 15keV; (c)fish brain2, 15keV; (d)SSIM and cross sectional lines of (a), (b) and (c).



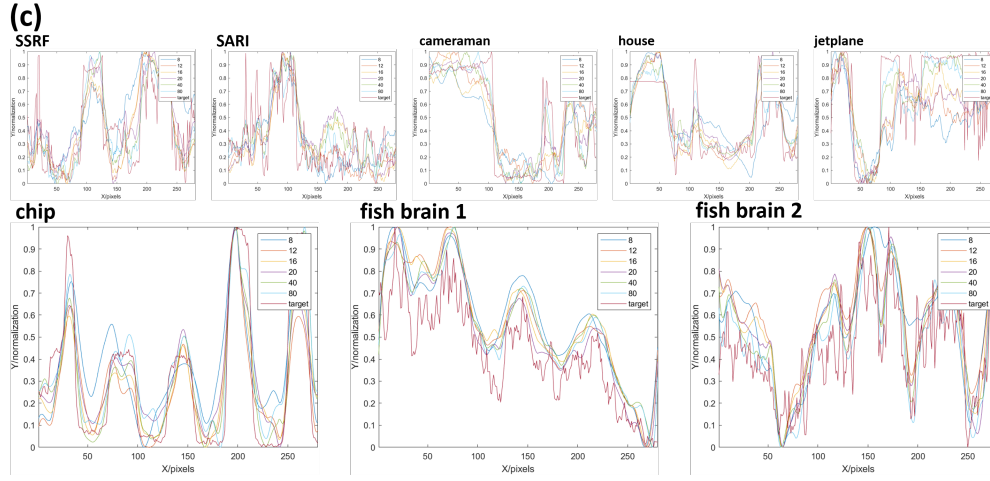


Fig. 7. Reconstruction results of GGI with ultra-low measurements(only 8).
(a)Experimental results; (b)Simulation results; (c)cross sectional lines

Finally, we demonstrate that GGI can reconstruct high-quality, large field of view results with only 100 measurements. Whether for a subsystem, namely traditional ghost imaging (40×40 , sampling rate 6.25%), or the entire bucket detector array (220×800 , sampling rate 0.000568%), the performance presented by GGI is astonishing. But this is far from the limit of the ability for global ghost imaging. A lower number of measurements means a lower X-ray ionizing radiation dose and a more efficient acquisition process, which has enormous value for the practical application of ghost imaging. So we will further demonstrate the high-quality reconstruction of GGI with ultra-low measurement numbers, as evidenced by Fig.7.

Multiple sets of objects in both experiments and simulation have proven that GGI can still reconstruct object images with only eight measurements! This is an ultra-low measurement count where other ghost imaging techniques have completely failed, or even collapsed. Global ghost imaging provides the conditions for low-dose imaging that is hundreds of times lower than X-ray standard imaging, and is expected to shorten the entire experimental process to within ten seconds or so.

4. Conclusion

In conclusion, we propose global ghost imaging method and provide a way to convert conventional GI methods to GGI, as well as a simpler and more universal reverse conversion method to convert the speckle patterns of GGI into GI form. We comprehensively and systematically demonstrate through simulation and experiments that GGI significantly improves the image quality of reconstruction results and eliminates the discontinuity between subsystems. Furthermore, we verify that global ghost imaging can also image large-sized objects at ultra-low sampling rates. This method is highly valuable in the field of medical imaging, and is also feasible for atoms, electrons, and neutrons. It has extremely high practical value, deep scalability, and broad application prospects. We believe that this study provides a new framework for ghost imaging, which will greatly accelerate the practical process of ghost imaging.

Funding. The National Key Research and Development Program of China (Grant Nos. 2022YFA1603601, 2021YFF0601203, 2021YFA1600703), the Young Scientists Fund of the National Natural Science Foundation of China (Grant No.12205361)

Acknowledgment. The authors thank WenJie Hao, Kang Du, Zenghao Song, JunXiong Fang, YanLing

245 Xue, Ke Li and FeiXiang Wang for their kind help and fruitful discussion on experiments and data process-
246 ing.

247 **Disclosures.** The authors declare no conflicts of interest.

248 **Data Availability Statement.** Data underlying the results presented in this paper are not publicly available
249 at this time but may be obtained from the authors upon reasonable request.

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